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Abraham Hertzberg
University of Washington
Seattle, WA 98195



Historical Overview and Current Program Efforts

Introduction

The following historical overview is designed for the convenience of the reviewer to trace the development of this program, which is devoted to exploring new energy conversion concepts that appear to have a particularly high payoff for NASA. The program has developed out of earlier programs which examined the potential of the laser for NASA as a fusion energy source for propulsion, an energy transmission device in space and, in particular, to develop energy conversion systems to convert laser radiation back into useful work. Over the years programs undertaken by the University of Washington for NASA have changed direction as NASA's mission capabilities in space have developed, until at present the program is largely directed

toward exploitation of new concepts of thermal management suitable for NASA's and the nation's needs.

Radiation Receivers

Several years ago the research team at the University of Washington was asked by colleagues at NASA to examine areas of energy conversion technology which showed promise of enhancing NASA's ability to convert laser or solar radiation into useful electrical energy. The preliminary studies were carried out by devising a model of a solar energy conversion system to examine the problems and advantages of high temperatures on energy conversion systems.¹ The study confirmed that a special receiver would be needed to suppress reradiation; otherwise receiver temperatures above 1500°K would be relatively inefficient due to blackbody reradiation.² The advantages of high temperature proved to be so attractive that a study of the physics of reradiation was carried out. These studies led to a new concept for radiation receivers in which the solar radiation was received in depth by a flowing gas in such a manner as to lead to the potential of extremely high temperatures within the receiver. It was shown that the reradiation could be trapped behind the colder gas entering the system so that the reradiation losses were minimized and efficient receivers working at up to as high as 3000°K are feasible in principle. In order to evaluate this potential, an experimental program was set up using a gaseous potassium system to demonstrate the process of radiation trapping and the potential of high efficiencies, as well as to provide a framework to test the technological feasibility of the system. This phase of our work has been successfully concluded with the achievement of the experimental conditions adequate to demonstrate the feasibility of radiation trapping as a method of

potentially increasing the efficiency of high temperature radiation receivers.^{3,4}

It should be pointed out that these findings apply not only to the trapping of solar radiation in useful working gases for proposed high temperature energy conversion systems but also equally well to the trapping of laser radiation provided that the proper gases are chosen. In addition, the efficient conversion of solar radiation into laser radiation via the solar-thermal-pumped lasers under study at the University under NASA grant NAG 1-176,^{5,6} and the potential of solar thermal photovoltaics⁷ to utilize the principle of a very high temperature blackbody cavity capable of recycling the photon energy, may benefit from the inclusion of the fundamental information developed. Furthermore, high temperature nuclear energy sources are equally capable of pumping these systems under conditions of proper shielding and the addition of a flowing gas system involving radiation trapping would increase the efficiency.

Liquid Droplet Radiation System

While relatively high efficiencies were predicted in these high temperature solar energy conversion systems,¹ the studies indicated that the addition of bottoming cycles operating at low temperatures provided even higher efficiencies (~70% conversion of incident radiation into available mechanical work). However, the necessity for the rejection of the remaining heat into space at relatively low temperatures implied a severe heat rejection problem. Our research group was also involved in the study of various thermal SPS concepts which also indicated that the chief limiting factor on solar thermal systems appeared to be the problem of thermal management.

The authors were impressed by the tendency of systems studies to optimize space energy thermal systems at relatively high temperatures due to the almost intractable problem of thermal management and heat rejection. After a period of preliminary analysis and studies carried out to examine waste management systems of various types, ranging from the conventional heat pipe to the more novel concepts which had been suggested historically, such as belt, disc and dust radiators,⁸⁻¹⁰ the authors concluded that a significant portion of their program should be devoted to developing concepts for thermal management in space.

The advantages suggested by the dust radiator concept of Dr. Hedgepeth's group at ASTRO Research indicated that in principle the very high surface-to-volume ratio of this system could be exploited to significantly reduce the mass of radiating systems. However, the difficulties in directing a cloud of dust particles and in transferring heat from the vehicle to the dust particles seemed intractable. At the same time, the authors became aware of the development of the ink jet printing process proposed by IBM,¹¹ in which a clever method of producing near-micron size ink droplets was developed which could be directed by powerful electrostatic fields to a sheet as a method of rapid printout. The ability to generate such carefully controlled droplets, plus the ability of a liquid to be in intimate contact with the heat exchanger tubes and remove the heat from the vehicle, suggested a direct extension of the liquid droplet principle to the design of an improved thermal management system in space. The drawback in such a system would be the potential of rapid evaporation of the droplets in exposure to the space environment. A study was therefore carried out by the students and faculty involved in this research which revealed that a variety of fluids are available which would meet the

requirements of a system embracing the technology of the liquid jet printer and be capable of a useful life.*

For example, liquid tin at temperatures even as high as 900°K would match and exceed the performance of heat pipes in this temperature range. In addition, the potential low weight of such a system spurred the study for other fluids such as eutectics of tin, lead and bismuth for lower temperatures. In particular, the utilization of known vacuum oils for the very low temperature heat rejection systems in space appears to be a new finding.

These studies were first reported by Dr. A.T. Mattick and Prof. A. Hertzberg in an IECEC paper in 1980¹² which discussed the important potential for this method of thermal management in space. The result of the theoretical analysis indicated that experiments were required to establish whether or not metallic liquid droplets of the desired diameter with viscosity and surface tension matched reasonably well with the projected future system could be produced reliably. Dr. Mattick developed an effective experiment which demonstrated that the basic principles of the liquid droplet ink jet printer could be applied to a wide variety of fluids. Mercury was selected as one of the early experimental fluids due to its extremely low melting point, which made it possible to carry out room temperature experiments which closely simulate the performance of liquid droplet radiators over a wide (350°K-950°K) temperature range.

*Thirty years was picked arbitrarily as a measure of useful life for proposed space systems.

The success of Dr. Mattick's experiments was particularly encouraging to the investigators. In consultation with the program managers of NASA, the main emphasis of the program was moved to exploit these findings as rapidly as possible. The liquid droplet radiator indicated the potential of heat rejection systems operating over a very wide temperature range and more than an order of magnitude lighter than competing heat pipe system. Indeed, liquid droplet systems appear particularly effective at low temperatures.

A study was also carried out of alternative concepts which utilized the principle of low vapor pressure liquids, such as "wet" belt radiators, wire radiators, and others. In addition, various new and modified concepts built around the liquid droplet principle were studied. While some of these alternate concepts offer a significant improvement over the conventional heat pipe radiator, the advantages of the liquid droplet radiator (LDR) appeared to be so overwhelming that it was decided to concentrate the efforts of this group on development of the liquid droplet concept. The findings of the group were subjected to peer review in various presentations and meetings in order to avoid any unforeseen problems and the feedback from these efforts were integrated into determining the directions for the most profitable avenues of research.*

*It is difficult to cover all the permutations and possibilities in such a system and the authors do not intend by this or any other previous presentation to imply that the concept, as evolved, is immutable in the face of continued research findings. The authors also do not intend to minimize the technological and practical difficulties involved in developing the LDR to its ultimate capability but rather feel that the potential improvements are such that the efforts involved imply such an improvement in the capabilities of NASA and the United States to manage thermal systems in space that it is proper to devote their best efforts in this direction.

In-depth studies were then undertaken of droplet emissivity, scaling properties of the droplet sheet,¹³ critical problem areas such as the design of effective structural containment, droplet aiming and dispersion, and manufacturing techniques. The potential of the LDR was also integrated into one of the investigators' teaching program in space systems design, in which the LDR was examined first as a potential "Getaway Special" as early as 1980. While such an experiment seemed feasible and proper at that time, the uncertain future of the Shuttle and the importance of the LDR indicated that programmatic enhancement efforts as well as an increase of the teaching component was needed. For example, in the winter quarter of 1981 the LDR was incorporated as part of the studies of the Aeronautics & Astronautics curriculum in space systems design. Test problems were assigned to the students related to the then accepted approach of the SP-100 system to explore the possibilities of increasing its power capabilities within the constraints of the payload volume and lifting capability of the Shuttle. It appeared that the LDR could be used to increase the 100 KW goal of the SP-100 concept to levels beyond 250 KW and the concept of deployable radiators was realized to be a specific and important aspect of the program. In the following year, specific study was made of various nuclear power space options utilizing an LDR to explore the potential of megawatt-size stations which could be lofted and deployed from the existing Shuttle.

This teaching program, considered highly challenging by the students, was well received by the better students and provided positive and important feedback to the research program. For example, the most recent study carried out by the students during the winter quarter of 1982 indicated that it is possible in principle to consider multimegawatt (1-10 MWe) space-based nuclear power modules which can be launched and deployed from the existing

Shuttle bay. While these studies are preliminary, the potential indicated by the students' exploratory point design appears to be beyond the capability of previously examined approaches.¹⁴ The author does not know of any other approach which offers a space-based power complex of multi-megawatt power, possibly as high as 100 MWe continuous, using only a few Shuttle launches.

Meanwhile, the basic studies of the LDR were proceeding rapidly and it was found that fundamental problems dealing with space charge effects and aerodynamic drag do not appear to offer any insurmountable technological difficulties. During the past year, at the invitation of the Air Force power group at the Rocket Propulsion Lab, an expanded study was carried out by the University in cooperation with the Energy Technology Group at Mathematical Sciences Northwest, Inc. The ability of the LDR to meet the anticipated space power needs of the Air Force, as well as NASA, has led to productive cooperation between these programs so that an enhanced effort can be carried out utilizing the manpower capabilities of the group at Mathematical Sciences Northwest and the University. In addition, a very effective working relationship has developed between the University and the NASA-Lewis group under the direction of Robert Bercaw, Head, Advanced Energetics and Power Systems Section, which adds to our capability in an important application of fundamental research, meeting both NASA's and the Air Force's requirement for space power in the near- and far-term.

The current interest of NASA in developing a permanent manned orbiting space station, capable of enhancing the scientific exploration of space but also intended to explore the potential of space industrialization, will create the need of systems capable of supplying high power continuously (25 to 250 KW). Multikilowatt power levels automatically imply a disposal

system capable of managing the waste heat plus an adequate energy storage system to provide power during the passage of the space station through Earth's shadow. Our current examination of the LDR indicates that by using a conventional solar collector and a thermal energy storage system a complete power supply and waste energy management system can be developed around the LDR. While this will be a subject of basic and applied research within our program during the coming year, it has also been targeted as a study problem for student efforts in the forthcoming 1983 winter quarter.

A more complete review of our current efforts in the liquid droplet heat rejection program is reported in a later section of this proposal which will review present status and plans for the forthcoming year.

Liquid Droplet Heat Exchangers

The preliminary systems assessment indicated that the concept of the LDR is extendable to heat exchangers which appear particularly suitable for space applications. The problem of highly effective, yet reliable heat exchangers has proved a problem which tends to dominate many space systems. For example, dynamic cycles involving Brayton engines are complicated by the requirements of heat exchangers. Indeed in any thermal power system the problem of developing an effective, lightweight heat exchanger of high reliability results in difficult design problems and systems compromises.

By employing the liquid droplet principle and the inherent low vapor pressure of the fluids, a direct contact heat exchanger working in zero G was believed to be possible. Preliminary studies carried out of the effectiveness and mass of such heat exchangers appeared very favorable. The liquid droplet heat exchanger was already being explored by our group under SERI contract XP-0-9371-1 and in a joint program with Mathematical Sciences Northwest through DOE contract #AC06-81-ER10918. These studies have

provided the basic groundwork of analysis on which we have been able to build the new concept for heat exchangers which, in particular, mate very well with the LDR.

The problems of zero G at first proved difficult and involved complex heat exchanger configurations which, while attractive in themselves, indicated the necessity of further exploratory development. At the present time, a number of configurations have been developed that are under both theoretical and exploratory experimental research at the University. These indicate that the liquid droplet direct-contact heat exchanger can work effectively in the zero G environment and greatly enhances the ultimate potential capability of the LDR.¹⁴ This section of our study is now moving in parallel with current studies of ultrahigh temperature heat exchangers being carried out for DOE and is, in and of itself, an important area of fundamental and applied research. As with the LDR, the current status of this aspect of our program and the plans for the forthcoming year will be discussed in more detail in later sections.

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